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► To cite this version:

Kevin Walsh, Juliette Knockaert, Katharina Dulias, Charline Giguet-Covex, Dianne Unsain, et al.. Bioarchaeological approaches to understanding the long-term development of mountain societies. *Archaeological and Anthropological Sciences*, 2023, 15, pp.199. 10.1007/s12520-023-01889-z . halshs-04378532

HAL Id: halshs-04378532

<https://shs.hal.science/halshs-04378532>

Submitted on 8 Jan 2024

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Bioarchaeological approaches to understanding the long-term development of mountain societies

Kevin Walsh¹ · Juliette Knockaert^{1,2} · Katharina Dulias^{1,3} · Charline Giguet-Covex⁴ · Dianne Unsain⁵ · Sylvain Burri⁶ · Pierre Magniez⁷ · Alistair Pike⁸ · David Orton¹ · Florence Mocci²

Received: 4 July 2022 / Accepted: 1 November 2023 / Published online: 1 December 2023
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Abstract

Archaeologists do not always differentiate between human activities, practices and techniques within landscape archaeology. This problem is reflected in some research into the development of pastoralism in the Alps. Here, we develop a framework within a “position paper” that engages with these different processes by assessing recent developments in bioarchaeological and palaeoenvironmental methods. Over the last two decades, alpine research has moved beyond the mere characterisation of human activities toward the classification and interpretation of specific practices and techniques, changing how we study the development of alpine pastoralism. Research into the development of mid-/long-distance transhumance from the Provençal plains to the Western Alps has generated considerable interest over the last 20 years. Therefore, the PATHWAY (Pastoralism, TransHumance in the Western Alps) project focuses on studying the Iron Age to Medieval pastoral systems in the Western Alps and south-eastern France, which is today one of the main regions in Europe where transhumant pastoralism still takes place. Finally, this contribution aims to review how bioarchaeological methods, combined with “cultural” archaeology, inform detailed quotidian aspects of lifeways rather than impactful, mediated generalising statements, such as mass population movements or simplistic generalisations about past diet.

Keywords Pastoralism · European Alps · Zooarchaeology · Isotopes · sedaDNA · Iron Age–Medieval

Introduction and context

Bioarchaeological methods are transforming our understanding of the development of alpine socioeconomic systems (Giguet-Covex et al. 2014; Grupe et al. 2017). As with many archaeological endeavours, the development of analytical frameworks and interpretations in alpine archaeology is a story of improving techniques that have allowed us to refine our knowledge of human lifeways, moving from broad characterisations of human activities in the past to the identification of specific practices. The 1990–2000s saw the development of several landscape archaeological projects in the mountainous regions of Europe, comprising surveys and excavations, an exploratory phase (Curdy et al. 1999; Davasse et al. 1997; Della-Casa et al. 2013; Ejarque et al. 2009; Galop 2016). Since then, this research evolved into interdisciplinary collaborations with palaeoenvironmental scientists considering relationships between climate change, human activity and concomitant impacts on vegetation and subsequent erosion. How we study high-altitude (European) alpine landscapes and the human activities that developed

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therein has improved radically over the last 15 years; nevertheless, there are still many challenges for the identification and characterisation of pastoral practices and techniques (Della-Casa et al. 2013; Reitmaier et al. 2018; Walsh et al. 2014). Despite the increased research activity in the Alps, only a small area of high altitudinal zones across the Alps has been studied.

The chronological and geographical foci of PATHWAY and, therefore, this article are the Iron Age to Medieval period in the Western Alps and south-eastern France, as this period is associated with the development of long-distance transhumance and regionally varying pastoralist practices that have so far eluded us. Here, we present our analytical and interpretive framework. We start with a discussion of the differences between human activities, practices and techniques within landscape archaeology and research into the development of pastoralism. This leads to a résumé of how research in alpine landscapes and pastoralism has developed over the last 20 years, comprising a brief synthesis of our early evidence, which allowed us to identify activities. This is followed by an assessment of how specific bioarchaeological and palaeoenvironmental methods have facilitated change in how we study the development of alpine pastoralism, moving beyond the mere characterisation of activities and moving toward the characterisation and interpretation of specific practices and techniques. At the time of writing, this project is still underway; this contribution's core aim is to propose an explicit framework, via a position piece, for investigating complex pastoral systems that integrate a wide range of data categories, a framework that we hope colleagues will find helpful in developing similar projects.

Defining activities, practices and techniques in pastoral systems

A pastoral system is a complex economic/livelihood system (Fig. 1) based on the interconnectedness of the breeder (and/or the shepherd/herder), herds/flocks, and the territories they exploit. The breeder's social, cultural, and ethnic identity, familial ties, and position in economic networks, on the one hand, and environmental, meteorological and climatic conditions, on the other hand, influence how they operate. Herd or flock composition and animal age are, in turn, strongly influenced by the demands of the trade and exchange system, from subsistence pastoralism to developed markets, which vary across time and space. An essential element in any pastoral system is animal fodder management, animals' eating patterns, and mobility patterns. In turn, the foddering system is structured around the territories' environmental characteristics available to the animals' owners; it is a process that shepherds and cow herders directly manage. Foddering and the exploitation

of primary and secondary products derived from animals must often follow a seasonal pattern, moving from one part of a region to another to benefit from the most productive pastures. Additionally, all the above change through time and continuous adaptation is necessary. Our interdisciplinary methodological approach allows us to highlight critical elements of this complex system of activities, practices and techniques (Fig. 2 and Table 1).

On its own, an individual data category often yields little interpretive value. In alpine landscapes, where archaeological evidence is particularly scarce, archaeological data require corroboration via various palaeoenvironmental data. One of the issues facing archaeologists and palaeoenvironmental scientists working in these areas (between c. 1600 and 2800 m a.s.l.) is the highly fragmentary nature of various datasets. Moreover, human–environment interactions operate at many spatial and temporal scales, and integrating these data in this complex spatiotemporal framework is often problematic.

The study of human activities, practices, and techniques is in part underpinned by data categories that operate at different spatial and temporal scales (Fig. 2). For example, climate models and broad-scale demographic proxies (sum probability distributions of radiocarbon dates, site numbers, and locations) provide continental or regional scale information; population movements, possibly influenced by climate change, may occur over several years or a generation or longer (Berger et al. 2019; Furholt 2018; Haak et al. 2015). Archaeological and palaeoenvironmental evidence are proxies for past human–environment interactions; in some instances, we can identify broad categories of economic activities, such as pastoralism, arable agriculture and mining. In other instances, one can identify actual practices, such as pasture creation via forest burning or the exploitation of specific animal species, based on proxies from natural archives (e.g. charcoal and lake sediment DNA) or the creation of structures for penning animals from archaeological proxies. Pasture use at high altitudes, and the culling of certain domesticates, is all “time-stamped” in one way or another; although it is not possible to assign a precise calendrical date to activities and practices, it is possible to infer seasons and moments within an annual round.

As with any archaeological, historical, or anthropological investigation, we must define which elements of human lifeways and processes we wish to examine. More specifically, we must identify the constituent elements of a pastoral system and how these elements manifest themselves in the archaeological record, e.g. animal bones, buildings/structures related to winter and summer flock/herd management, transhumant routes, areas of pasture, artefacts associated with pastoralism—from pottery to shears.

Activities might be defined as broad notions or categories of *what* (productive/economic activity) people have

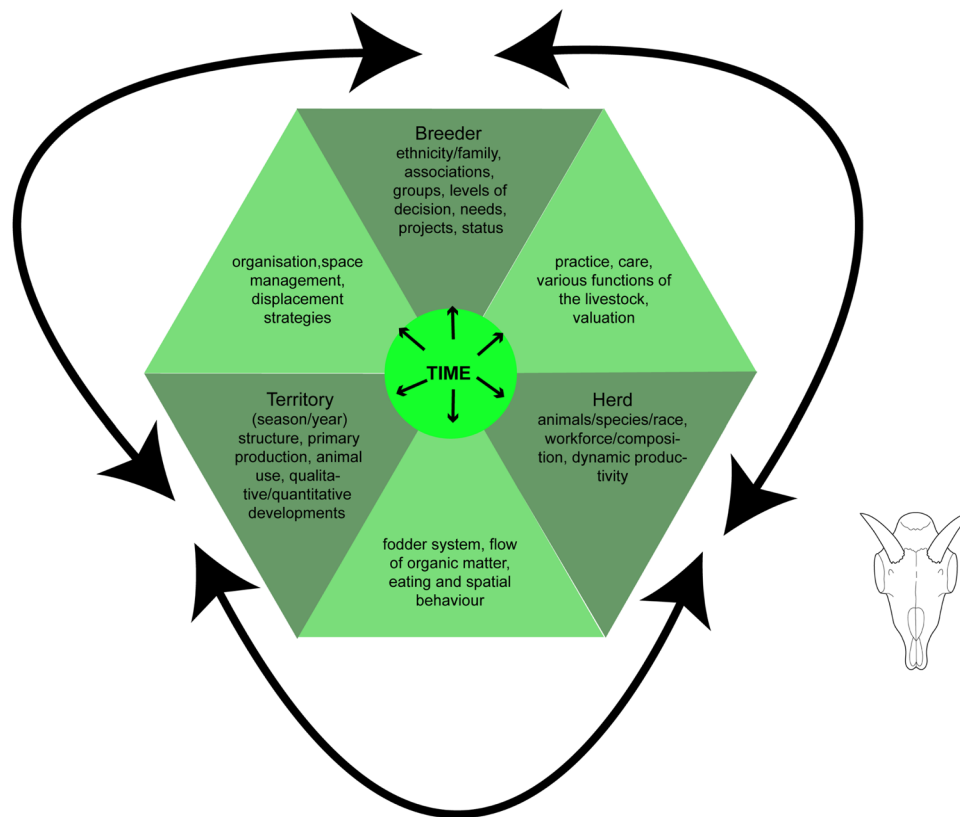


Fig. 1 Adapted from Lhoste (1984). A pastoral system comprises a range of interconnected processes; relationships between the breeder, the pastoral territory and animals within the pastoral system. These constituent elements in the pastoral system (breeder and/or decision-making authority, e.g. seigneurial or local power during the Middle Ages (Moriceau 2005; Burri 2019), flock/herd and territory) and the methodologies applied in this project. The study of historical records permits the investigation of social, cultural, and economic structures, in some instances, the identity of the breeder. These all influence

flock/herd management. The use of stable and radiogenic isotopes and zooarchaeological analyses permit the assessment of flock/herd composition and how the animals were exploited. The key task of foddering animals is influenced by complex social, economic, and environmental/climatic variables that control which pastures are used and when. Moving back to the top of the figure, we see how our understanding of the management and control of pastoral spaces and transhumance needs to incorporate an interrogation of sociocultural processes via documents (where available)

developed, i.e. managing sheep/goats/cattle for either primary or secondary products.

Practices might be defined as broad routines, systems, or behaviours. For example, animal slaughter at a certain age or time of year, moving animals from one pasture to another, sheltering animals in buildings during the winter in lowland areas, sheltering young or sick animals in enclosures in the summer on high-altitude pastures, choosing specific types of topography/landscape-types for pasture.

Techniques might be defined as the precise enaction of a given practice—e.g. building an animal enclosure in a specific manner, milking an animal in a particular place, using a particular process to make cheese (with a specific type of pottery), killing and butchering an animal a particular manner. We recognise that techniques comprise behaviours as well.

Early methodological and interpretive frameworks in alpine archaeology in the Western Alps

Early research and interpretations in alpine archaeology operated at broad spatial scales, assessing the long-term fluctuations in human movements into the high-altitude zones (Curdy 2007; Curdy et al. 1999; Della Casa 2007; Della Casa et al. 1999; Martin et al. 2012; Mocci et al. 2005). These interpretations were founded on the identification, excavation and dating of archaeological sites, material culture, and ecofacts. The assessments of this evidence are often supported by broad-scale palaeoecological work, especially palynology, which facilitated the identification of phases of pastoralism (NPPs, nitrophilous plants, etc.) (Dietre et al. 2014; Schwörer et al. 2015, 2014; Wick

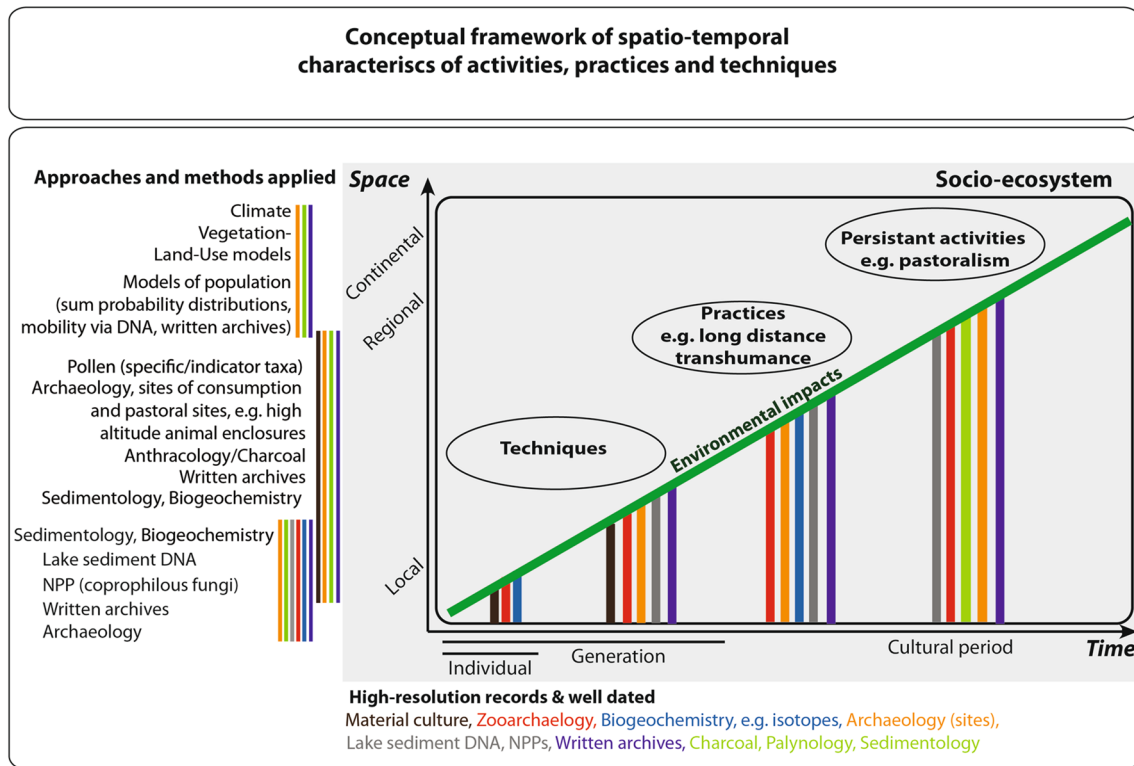


Fig. 2 Most landscapes are the product of imbricated environmental and cultural processes that operate at different spatial and temporal scales. Here, we characterise some key processes and associated data categories, which are colour-coded, and suggest how these relate to the investigation of activities, practices, and techniques. The figure is structured around simple notions of temporal and spatial scales. Certain processes might function across broader temporal and spatial scales, such as climate change and human migrations. We can also situate persistent activities within this scale that we know existed for several centuries, but we might not be aware of the specific practices or techniques that constitute those activities and may have changed during the phase of persistent activity. Activities might be defined as broad notions or categories of what (productive/economic activity)

people have developed, i.e. managing sheep/goats/cattle for either primary or secondary products, burning woodland for pasture creation. Moving toward the bottom left-hand corner of the figure, the middle-range scales and the associated suite of methods facilitate the interrogation of certain practices, such as burning woodland for pasture creation. In the bottom left-hand corner, the final scale is that of techniques. Techniques might be defined as the precise enaction of a given practice—e.g. building an animal enclosure in a specific manner, milking an animal in a particular place, using a specific process to make cheese (with a particular type of pottery or wooden vessels), killing and butchering an animal in a specific manner. We recognise that techniques comprise behaviours as well

and Tinner 1997). One spatially specific practice that was successfully identified during the early phases of research was the clearance of the forest using fire, inferred from anthracological investigations (Carcaillet and Brun 2000; Talon 2010).

During the 1990s and early 2000s, some broad chronological trends and activities were successfully identified, but identifying specific forms of transhumant pastoralism and specific practices eluded researchers. The discovery of numerous stone structures across several high-altitude areas (1800–2400 m a.s.l.) in the French Alps allowed the creation of basic distribution maps. The excavation and dating of a sample of these permitted the elucidation of chronological phases of activity. Perhaps the most important discovery is the evidence for the first stone-built structures, interpreted as enclosures for domestic animals, appearing from about 2500

BC (Walsh et al. 2014; Walsh and Mocci 2011). However, due to soil acidity, the scarcity of the faunal remains in many parts of the Alps meant that assertions regarding the pastoral function of the often isolated stone-built structures were tentative, although, in all probability, legitimate. Grouped structures were also identified and, depending on the places and periods of occupations, permitted the interpretation of resources and activities that required numerous people, such as hay-making (Burri et al. 2018). Such grouped structures can also be associated with combined mining and pastoral activity, part of a subsistence strategy/self-sufficient economy, hosting several families (Guffond and Melo 2018).

The almost complete absence of faunal remains on mid- and high-altitude sites also meant that archaeologists were unable to engage with the temporal and spatial variations in flock/herd composition, i.e. identify when the current

Table 1 The relationship between scales at which human societies/lifeways/socioecosystems function and data categories and cultural/historical/archaeological inferences relating to human activities, practices, and techniques

Scale	Data types	Examples of possible inferences	Bibliographic references
Continental-scale (biogeographic realm) cultural processes that may take place over several years or over a generation or longer	<ul style="list-style-type: none"> -Climate (e.g. isotopes, pollen), broad cultural processes (e.g. genetic data and chronologies) -Zooarchaeological evidence 	<ul style="list-style-type: none"> -Arrival of new populations with new economic systems or attitudes toward the use of mountain landscapes -Changes in vegetation, length of grazing season due to climate changes -Change in faunal spectra/morphology across a region suggesting the arrival of a new economic system 	<p><i>Climate</i>: Kaufman et al. 2020; Magry et al. 2004; Maise 1998 <i>Migration/population change</i>: Allentoft et al. 2015; Schlumbaum et al. 2003; Haak et al. 2015; Furtwängler et al. 2020; Trixl 2022</p>
Changes at the regional scale (ecoprovince or bioregion, “massif”, i.e. a recognised mountainous region, such as the Ecrins), e.g. new economic activities/impact on the environment	<ul style="list-style-type: none"> -Palynology -Sedimentology—geochemistry (large lake—catchments) -Archaeological site numbers and locations -Zooarchaeological evidence -Archival documents 	<ul style="list-style-type: none"> -Changes in vegetation due to environmental change or human activity—e.g. grazing -Pastoral of archaeological sites suggestive of pastoral economy -Faunal evidence from sites located in the same region suggesting presence and/or preference for certain species -Ancient animal enclosures suggesting penning of animals 	<p><i>Vegetation, geosystem</i>: Arnaud et al. 2012; Rapuc et al. 2021 <i>Fauna</i>: Gastra 2014; Gardeisen 2013; Greenfield 1999; Jiménez-Manchón et al. 2020; Lespes et al. 2019; Leveau and Segard 2004; Nieto-Espinet et al. 2020; Trentacoste et al. 2018; Valenzuela-Lamas and Albarella 2017</p> <p><i>Landscape archaeology</i>: Della Casa 2007; Della-Casa et al. 2013; Walsh and Mucci 2016 <i>Pedoanthracology</i>: Carcaillet and Brun et al. 2022; Talon 2010 <i>sedDNA</i>: Garcés-Pastor et al. 2019; Pansu et al. 2015; Sabatier et al. 2017 <i>Biomolecular analyses</i>: Schroeter et al. 2020</p>
Micro-regional (ecozone, local (valley, catchment)) scale changes—evidence for activities and some practices. Seasonal activities, e.g. use of high-altitude pasture and impact on the environment	<ul style="list-style-type: none"> -Landscape archaeology—site distributions, charcoal, bone -Pedoanthracology across the valley, landscape transects -Lake sedaDNA (plants and mammals), coprophilous fungi, specific biomarkers, e.g. coprostanol -Sedimentology/geochemistry (small lakes—catchments) -Archival documents 	<ul style="list-style-type: none"> -Valley/pasture-scale evidence for burning -Detection of nitrophilous and ruderal vegetation, which may indicate specific practices like the presence of animal stalls (“repositoir”) -Indirect detection of herbivores, which provides quantitative information on stock density and thus pastoral pressure -Direct detection of animals in the lake catchment, providing knowledge on animal composition in pastures -Impacts of vegetation, soils and erosion -Isotopic evidence for landscape opening -Characterisation and quantification of animal flows -Social and economic structure of pastoralism and transhumance 	<p><i>Coprophilous fungi</i>: Etienne et al. 2015; Giguet-Covex et al. 2019; Garcés-Pastor et al., 2022 <i>Sedimentology/geochemistry</i>: Giguet-Covex et al. 2011; Bajard et al. 2017a,b</p> <p><i>Isotopic evidence for landscape opening</i>: e.g. Drucker et al. 2008; Doppler et al. 2017 <i>Written archives</i>: Burri 2019; Cesarini et al. 2018; M Segard 2009a</p>

Table 1 (continued)

Scale	Data types	Examples of possible inferences	Bibliographic references
Point-specific scale for certain agricultural practices and techniques, including seasonal stocking of animals, use of specific areas during certain months, e.g. “quarters d’aout”, i.e. seasonal pasture used at specific times of the year Milking, cheese production at certain times of the year	<ul style="list-style-type: none"> -Certain archaeological sites/material culture (e.g. pottery, strainers) -Zooarchaeological evidence -Stable isotopes from animal remains -Molecular and stable isotope analyses of lipids from specific types of pottery -Archival documents 	<ul style="list-style-type: none"> -Faunal evidence with age profile, size of animals, sex data suggesting specific pastoral practice (e.g. meat, milk, wool, traction) -Discovery of ceramics related to cheese production or objects related to the exploitation of wool such as shears for the removal of fleeces, spindle whorls or weights 	<ul style="list-style-type: none"> <i>Age profiles</i>: e.g. Chiquet and Reynaud Savioz 2019; Schibler and Schlumbaum 2007; Schlumbaum et al. 2003 <i>Dairying and cheese production</i>: Carrer et al. 2016 <i>Herdin strategies</i>: e.g. Gerling et al. 2017 <i>Specific goat breeding contracts for dairy products in mountain areas</i>: Burri 2019 <i>Material culture</i>: Mouton 2008

division of cattle in the north and sheep/goat in the south (Drogue 1950; Mahaut 1940) emerged or if there have been periods in the past when this division existed. It is important to remember that palynology (pollen and spore of coprophilous fungi) only provides indirect evidence of pasturing, unlike sedaDNA, which allows the identification of specific domesticates.

Questions that have been difficult for alpine archaeologists to answer

When we first designed the Southern French Alps Landscape Archaeology Programme in 1998, we aimed to test the hypothesis that long-distance transhumance developed in the region during the Roman Period. Indeed, the discovery, in the 1990s, of several large Roman sheepfolds in the Crau plain in Western Provence led to considerable discussion concerning the Roman origin of large-scale pastoralism and possible transhumance in south-eastern France (Badan et al. 2006, 1995; Leveau 2006; Leveau and Segard 2006, 2004; Saatkamp et al. 2021). Inspired by the work of Philippe Leveau and his interrogation of a notional long-distance transhumant system with winter pasturing on La Crau and summer pasturing in the Alps, an initial aim of our research was to search for Roman period pastoral sites at high altitudes in the French Alps (Mocci et al. 2005; Palet-Martinez et al. 2003; Maxence Segard 2009a, b; Walsh and Mocci 2011, 2016; Walsh et al. 2010). However, archaeological and environmental investigations in two different areas of the Southern French Alps (Ubaye Valley and Ecrins massif) underlined the absence of human/pastoral occupation evidence in the mid/high-altitude zones during this period. However, the absence of archaeological evidence does not necessarily mean an absence of activity in the past but could be the consequence of different activities and practices, e.g. “invisible” shepherds vs “visible” dairymen/women, i.e. the activities associated with dairy production tend to leave archaeological traces while shepherding might be archaeologically “invisible” (Carrer 2016a, b). In the North Western Alps, there are clear sedaDNA signals for pastoral activity during the Iron Age and Roman period, while there are relatively few archaeological sites dated to these periods (Bajard et al. 2020; Giguët-Covex et al., 2014; Rey et al. 2008).

By the mid-2000s, we possessed an extensive set of archaeological site data and palaeoecological evidence from the high-altitude zones that provided a compelling characterisation of some aspects of a potential transhumant pastoral system, i.e. the location and use of summer pastoral areas. To interrogate a transhumant system’s development, we needed to review evidence from sites that consumed animal products (primary and secondary products) derived from husbandry practices.

Understanding the development of transhumance from the bottom upwards

Spatially, a transhumant system is constituted by nodal zones exploited at different times of the year. The distance between these nodal zones can vary from a few kilometres to more than 100 km (Brisebarre 2013; Costello et al. 2018; Davies 1941). The movement between both can go in two directions according to the position of the home residence of the flock/herd: from the Alps to the lowlands for winter grazing and from the lowlands to the Alps for summer grazing. Beyond this pendular movement, the complexity of pastoral movements and the existence of intermediate zones must also be taken into account. Settlements such as “granges” (low-altitude farmsteads with barns), occupied mainly in spring and autumn, i.e. before entering summer pastures and before winter migration or wintering in barns, are also structural elements of the transhumant system (Malle 1999; Le Roy et al. 2017). Earlier, we highlighted some evidence associated with the high-altitude, notionally summer, pastoral activities. The other end of the system can be the principal residence or the stable, notionally, late-autumn to spring pastoral zone and possible stables. We can assume that many lowland areas were exploited for grazing and animal fodder production, but identifying the areas used at different moments in the past is difficult, especially the actual pastoral sites themselves (Burri et al. 2018; Burri and Durand 2021). However, some Roman pastoral zones have been identified. For example, the Crau, mentioned above, is a vast alluvial plain underlain by quaternary stone/pebble deposits. There were significant Roman economic and settlement activity levels in the area, including sheepfolds (Badan et al. 2006, 1995). However, we do not know if Roman animals were moved from here to alpine pastures during the summer. The “Great Transhumance”, which comprises seasonal mobility of several thousands of domestic livestock from the plains of Western Provence (for instance, La Crau) to the alpine pastures, certainly occurred between the eighteenth and mid-twentieth centuries; the study of the medieval written archives reveals its roots and also highlights the diversity of mobility patterns between the Provence and the Alps during the medieval period (Burri et al. 2018).

Accepting that many areas would have served as lowland pasture, the most significant element within the pastoral system is, of course, the animals themselves and the associated stories of birth, life and death—i.e. how animals were managed and exploited; *birth*—when and where animals were born and weaned; *life*—which secondary products were exploited and when and how animals were pastured, including the all-important transhumant movement between lowland and upland pasture; *death*—when and why animals were slaughtered and exploited for the primary product, i.e. meat.

Previous zooarchaeological studies

From the Neolithic to the medieval period, many social, political and economic changes affected, directly or indirectly, animal husbandry strategies. Husbandry strategies were not uniform and were contingent upon socioeconomic and environmental contexts. Numerous zooarchaeological data analysed over the past 50 years across the wider Western Alps and the abutting lowland areas provide basic information about diet, culinary and ritual practices. In a general trend, from the Neolithic to the Late Iron Age, the husbandry systems were mainly focused on caprine, i.e. sheep and/or goat, cattle and pig, with caprine predominance (Reynaud Savioz et al. 2018; Blaise 2005; Blaise et al. 2010; Bréhard 2011; Chiquet and Reynaud Savioz 2019; Columbeau, 2002a, 1991; Garcia 1995; Helmer 1991; Helmer et al. 2005; Helmer and Vigne 2004; Latour et al. 2009; Leguilloux 1995, 1989; Méniel 2019; Pellegrino and Rodet-Belarbi 2006; Rodet-Belarbi 2003, 2001; Rodet-Belarbi et al. 2007; Vigne and Helmer 1999; Vuillien and Gourichon 2019). This predominance of caprine over the long term is particularly significant in the Mediterranean area (Duval et al. 2017) and differs from the pattern observed across the Alps. To the north of the Po River, where the relative abundance of sheep/goat decreased during the Late Bronze Age, cattle replaced them as the dominant species (Trentacoste et al. 2018). The emergence of urbanisation during the Iron Age, and then the Roman conquest of Transalpine Gaul, brought significant changes in local socioeconomic structures, including animal husbandry strategies. For example, there was a high level of pig exploitation in urban areas (Columbeau 2002b; Rodet-Belarbi 2013).

However, newly acquired zooarchaeological data for the medieval period in Provence nuances this homogeneous view of the animal economy over time. Indeed, between the tenth and twelfth centuries (and perhaps earlier), social status largely influenced breeding practices. Modest groups (peasants and urban dwellers) mainly bred caprines, while wealthy populations (at least in the countryside) favoured pigs (Unsain et al., 2023). It is only from the thirteenth century onwards that sheep farming took on an importance that continues to this day (Aubron et al. 2015). At that time, this expansion was directly linked to the development of the wool industry (Burri et al. 2018; Unsain et al., 2023).

Despite our broad understanding of species proportions and preferences, we know relatively little about the management of the animals, especially possible transhumant systems. Zooarchaeological evidence does allow us to consider some hypotheses regarding seasonal livestock mobility in south-eastern France since the Neolithic; in particular, the analysis of caprine slaughter profiles from sheepfold-cave sites suggests seasonal occupation and livestock mobility between complementary settlements (Helmer et al. 2005).

Results of multidisciplinary studies involving anthracology, archaeology, and geoarchaeology support the interpretation of a pastoral function of the caves in south-eastern France and the Northern French Alps (Brochier et al. 1998; Delhon et al. 2008; Martin et al. 2021; Nicod et al. 2010, 2008). For more recent periods, only a few zooarchaeological data detailing pastoral occupations in caves or high-altitude sites have been published (Guffond and Melo 2018; Latour et al. 2009; Reynaud Savioz 2016; Rodet-Belarbi et al. 2007; Gangi et al. 2015; Mascarello 2014; Sartorio et al. 2014). The discovery of sheep and lamb skeletons trapped during the Second Iron Age in the Gouffre de Giétroz Devant, at an altitude of 2178 m in the Valais Alps, provides the earliest evidence to date of livestock mobility in the alpine pastures, within the study area (Reynaud Savioz et al. 2018).

Moving from the description of activities to the study and interpretation of practices and techniques

Having established the critical themes dealt with by earlier research, we now consider a framework for investigating the practices and techniques that constituted the earliest forms of transhumant pastoralism in the Western Alps. Key questions relating to practices and techniques are as follows:

- What was the composition (species mix) of flocks and herds in the study areas, and what were these animals used for (mortality profiles)?
- Were these animals moved seasonally from one region to another? If so, what were the origin and destination points for these movements (i.e. winter and summer pastures)?
- At what moments in the past was this system employed, and did it vary over time? What variations were there in herding strategies in local mountain husbandry systems (foddering practices, short-distance mobility)?
- Which specific high-altitude zones were exploited for pasture, and which domesticates were present?
- What impact did pastoral activity have on the “natural” ecosystem and the geomorphic system?

Recent developments: the “bioarchaeological revolution”

Research in Europe’s mountains, including the Alps, has increasingly used modern bioarchaeological methods. Using a suite of recently developed techniques, we can now consider some specific characteristics of early pastoral systems. Below, we assess our key data categories: faunal analysis and sedimentary DNA (Fig. 3 and Table 2). We review their respective contributions to our interrogation of transhumant

pastoralism’s history and then contextualise this within a brief overview of pertinent archaeological and historical evidence.

Review of recent approaches in zooarchaeology

Distinguishing sheep and goat: a review of the production and herding strategies

Over the last 50 years of faunal studies in the Western Alps and the abutting lowland Provençal areas, zooarchaeologists have tended to group sheep and goat remains within the so-called “sheep/goat” or “domesticated caprine” class. This reflects the fact that sheep and goats have very similar skeletons (Salvagno and Albarella 2017). Therefore, before the 2000s, only a few morphological criteria distinguishing these species were published (Boessneck 1969; Payne 1985; Prummel and Frisch 1986; Rowly-Conwy, 1998). Payne (1985) proposed the first criteria based on deciduous teeth and first molar in juvenile specimens. Moreover, taphonomic processes (fragmentation, alteration of the bone surfaces) and the age of the animal (unfused bones, tooth wear) can affect the identification criteria reliability (Zeder and Pilaar 2010). Finally, logistical issues, especially time in the context of short-contract rescue archaeology, can hinder accurate identification.

The critical issue is that sheep and goats have different roles/uses in a pastoral system. During the last decade, zooarchaeological reviews of the morphological criteria on several series of Neolithic caprine mandibles and lower teeth in south-eastern France have highlighted that sheep and goats were used for different production strategies: sheep were mainly exploited for their meat while goats were more generally used for milk (Blaise 2005; Blaise et al. 2010; Helmer et al. 2005; Helmer and Vigne 2004; Vigne and Helmer 2007). Furthermore, despite their morphological similarities, sheep and goats have different physiological needs and feeding behaviours: Sheep are primarily grazers, while goats tend to browse (Balasse and Ambrose 2005; Toussaint 2011, 2001). This difference is significant because herding strategies for these two species could have resulted in the exploitation of different vegetation types (pasture, understorey or brushwood), although the two animals could be present simultaneously in the same area.

Our research reviews the identification of caprines from key sites from the Iron Age to the Medieval period (Fig. 3 and Table 2) by combining the analysis of the morphological criteria on mandibles and mandibular teeth (Balasse and Ambrose 2005; Gillis et al. 2011; Halstead et al. 2002; Helmer 2000; Payne 1985; Zeder and Pilaar 2010) and collagen peptide analysis (ZooMS: Zooarchaeology by Mass Spectrometry). The latter, developed by Buckley et al. (Buckley et al. 2010), allows the distinction between

Table 2 Sampled sites, their location, function, altitude, period and operation supervisors

Site no	Location	Site name	Site type	Altitude	Period	Excavators
1	Fontvieille (France)	Montpaon	Fortified village and castle	230	Middle Ages	J.-C. Treglia, V. Rinalducci, M.-L. Laharie, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS
2	Eyguieres (France)	Saint Pierre	<i>Villa</i> —rural settlement	150	Antiquity—Early Middle Ages	J.-P. Pelleter, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS
3	Lamanon (France)	Verdelet 1	Castle	167	Middle Ages	A. Constant, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS
4	Aix-en-Provence (France)	Sextius-Mirabeau	Urban settlement	185	Antiquity	N. Nin, Direction Archéologie et Muséum d'Aix-en-Provence
5	Aix-en-Provence (France)	Entremont	<i>Oppidum</i>	370	Iron Age	P. Arcelin, G. Congés, Centre Camille Jullian Aix Marseille Université-CNRS & Service Régional de l'Archéologie Provence Alpes Côte d'Azur
6	Puylobouier (France)	Richaume 1	<i>Villa</i>	320	Antiquity	F. Mocci, Centre Camille Jullian Aix Marseille Université-CNRS
7	Cadenet (France)	Le Castellar	Fortified settlement	350	Iron Age—antiquity	547 mD. Isoardi, Centre Camille Jullian Aix Marseille Université-CNRS
8	Allemagne-en-Provence (France)	Notre Dame	Seigneurial fortified residence, peasant habitat	547	Middle Ages	D. Mouton, M. Varano, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS & Groupe de Recherche d'Histoire, Université de Rouen
9	Allemagne-en-Provence (France)	La Moutte	Castle	520	Middle Ages	D. Mouton, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS
10	Niozelles (France)	Grande Bastide	Castle	450	Middle Ages	D. Mouton, Laboratoire d'Archéologie Médiévale et Moderne en Méditerranée, Aix Marseille Université-CNRS
11	Castellane (France)	Petra Castellana	Town	860	Middle Ages	V. Buccio, Service Départemental des Alpes de Haute-Provence
12	Les Mujouls (France)	Col d'Adon	High-altitude rural site	1000	Antiquity	R. Golosetti, Centre Camille Jullian, Aix Marseille Université-CNRS
13	Roubion (France)	Cime de la Tourmerie	Fortified place of worship	1815	Iron Age	F. Suméra, Service Régional de l'Archéologie Provence Alpes Côte d'Azur & Centre Camille Jullian
14	Jausiers (France)	Tertre des Sagnes	<i>Brandopferplätze</i>	1990	Iron Age	D. Garcia, Centre Camille Jullian, Aix Marseille Université-CNRS

Table 2 (continued)

Site no	Location	Site name	Site type	Altitude	Period	Excavators
15	Le Bourg-d'Oisans	Lauvitel	High-altitude pastoral site	1570	Middle Ages	F. Mocchi, Centre Camille Jullian, Aix Marseille Université-CNRS
16	Seez (France)	Col Petit Saint-Bernard	High-altitude Roman site	2180	Antiquity	S. Crogiez-Pétrequin, Université de Tours
17	La Thuile (Italie)	Ongères	Rural settlement	1665	Middle Ages and post	G. Di Gangi, Ch.-M. Lebole, Dipartimento di Studi Storici, Università di Torino
18	Quart (Italie)	Castello di Quart	Seigneurial fortified residence	740	Middle Ages	L. Apollonia, Dipartimento Soprintendenza per i beni e le attività culturali della Valle d'Aosta
19	Nus (Italie)	Messigne	Rural settlement	680	Antiquity	A. Armirotti, Dipartimento Soprintendenza per i beni e le attività culturali della Valle d'Aosta
20	Graines (Italie)	Castello di Graines	Seigneurial fortified residence	1320	Middle Ages	G. Sartorio, Dipartimento Soprintendenza per i beni e le attività culturali della Valle d'Aosta
21	Sixt-Fer-à-Cheval (France)	Alpage de Sales	High-altitude hut	1710	Middle Ages	C. Guffond, Unité archéologie et patrimoine bâti, Conseil départemental de la Haute-Savoie
22	Evionnaz	Gouffre de Giétroz Devant	Natural trap	2178	Iron Age	M. Blant et N. Reynaud Savioz, Institut suisse de Spéléologie et de Karstologie et ARIA SA
23	Savièse (Suisse)	La Soie	High-altitude village	872	Neolithic	D. Baudais, Laboratoire d'archéologie préhistorique et anthropologie, Université de Genève, collaborateur externe
24	Gamsen (Suisse)	Brig/Glits	High-altitude villages	670	Iron Age to Middle Ages	A. Benkert, C. Epiney-Nicoud: Archéologie et Recherches Interdisciplinaires dans les Alpes
A	La Roche de la Rame (France)	La Roche-de-Rame	Lake	945	Diachronic	2284 m, C. Gignot-Covex, Laboratoire EDYTEM (Environnement Dynamique et Territoire de Montagne), Université Savoie Mont Blanc
B	Argentera (France)	Maddalena	Lake	1974	Diachronic	C. Gignot-Covex, Laboratoire EDYTEM (Environnement Dynamique et Territoire de Montagne), Université Savoie Mont Blanc
C	Larche (France)	Lauzanier	Lake	2284	Diachronic	C. Gignot-Covex, Laboratoire EDYTEM (Environnement Dynamique et Territoire de Montagne), Université Savoie Mont Blanc

Table 2 (continued)

Site no	Location	Site name	Site type	Altitude	Period	Excavators
D	Passy (France)	Anterne	Lake	2063	Diachronic	C. Gignuet-Covex, Laboratoire EDYTEM (Environnement Dynamique et Territoire de Montagne), Université Savoie Mont Blanc
E	Passy (France)	Laouchet	Lake	1948	Diachronic	C. Gignuet-Covex, Laboratoire EDYTEM (Environnement Dynamique et Territoire de Montagne), Université Savoie Mont Blanc

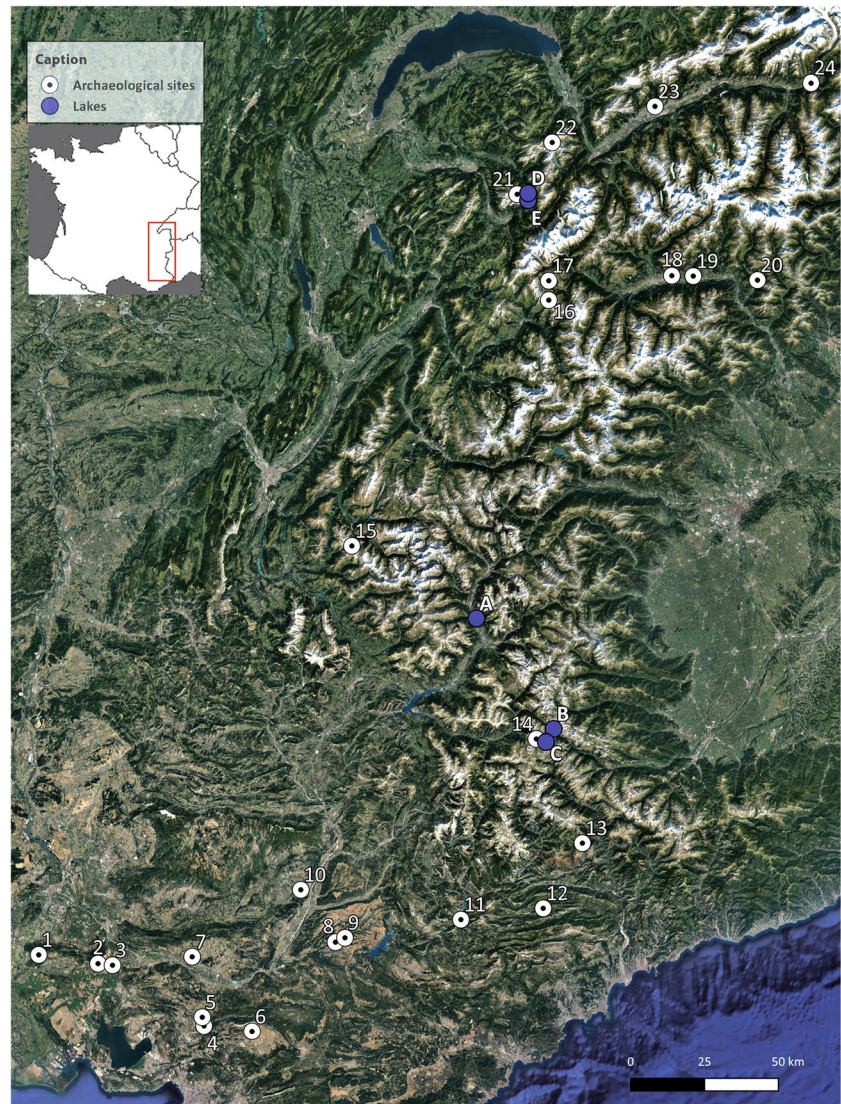
sheep and goats by analysing a single collagen peptide from archaeological bone or tooth root when teeth are isolated. The significant advantages of this method are that it only requires a small sample from the bone (c. 15–30 mg), and it is cheap and can therefore be used on large zooarchaeological collections. However, it cannot distinguish sheep (*Ovis aries*) from chamois (*Rupicapra rupicapra*), nor goat (*Capra hircus*) from ibex (*Capra ibex*) (Buckley et al. 2010; Welker et al. 2016). In addition, ZooMS must be employed with complementary observations of the morphological characteristics of the bones. Combining these methods allows the evaluation of sheep and goat frequency within archaeological contexts, thereby refining mortality profiles. The recent improvements in the statistical analysis, representation, and comparison of mortality profiles (Gerbault et al. 2016) allow us to investigate production strategies associated with the two species and thereby review changes and specialised pastoral strategies across time and space. Moreover, the distinction between sheep and goat and the characterisation of mortality profiles may help identify the wool economy's emergence in Gallia Narbonensis (Congès and Leguilloux 2012; Frayn 1984; Leguilloux 2003). For the Late Medieval period, historical resources show that goat frequencies were relatively high within mixed flocks from the XII to the XIVth centuries in the Provençal plains and South Alpine regions, where they constituted about 22% of the livestock (Burri 2019). While many have assumed that the sheep were predominant, these new analytical tools allow us to review the sheep and goat ratios and reassess the role of the goat in the local economy.

Transhumant mobility

Investigating transhumant mobility using isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$)

As successful pastoralism is often underpinned by strategies that render potentially unproductive land productive by moving animals away from the best arable areas into areas unsuitable for growing crops, investigating the evolution of this strategy is essential. Consequently, one of the key challenges for the archaeology of pastoralism is the development of modern techniques that facilitate the investigation of herding strategies, especially the ability to distinguish long-distance mobile systems and local herding, including short-distance vertical mobility. In addition, the aim is to distinguish those animals with remote origins (e.g. trade) and highlight alpine grazing and foddering resource management. To this end, the intra-tooth sequential isotope analysis of domestic herbivores (caprines and cattle) seems to be one of the most promising approaches.

Fig. 3 General map of the study area with the locations of the sampled sites (white circles) and sampled lakes (blue circles). Site names are provided in Table 2



Over the last two decades, measurements of strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) have been widely used by archaeologists in the assessment of the origin and mobility of past human and animal individuals/populations between different geological areas (Balasse et al. 2002; Bentley 2006; Bogaard et al. 2014; Evans et al. 2007; Gerling et al. 2017; Minniti et al. 2014; Pellegrini et al. 2008; Reitmaier et al. 2018; Valenzuela-Lamas et al. 2016; Viner et al. 2010). The $^{87}\text{Sr}/^{86}\text{Sr}$ signal recorded in tooth enamel mostly depends on the geological environments and feeding grounds frequented by the animal (Lewis et al. 2017). It is assumed the strontium signal is recorded during tooth formation with little subsequent change. Therefore, sequential intra-tooth analysis following the growth axis of specific teeth (second and third lower molars) should provide chronological information about the different geological areas frequented by the animal during the first years of its life. Nevertheless, an obvious challenge with the method and our ability

to identify provenance and mobility is, on the one hand, the determination of local bioavailable Sr isotope composition as well as the identification of the possible areas of provenance (Burton and Price 2013). To this end, several Sr ratio maps based on bioavailable and/or non-bioavailable samples have been produced in different regions of the world over the last decade (e.g. Bataille et al. 2018, 2020; Bataille and Bowen 2012; Evans et al. 2010; Hartman and Richards 2014; Voerkelius et al. 2010) and especially in France (Willmes et al. 2014) and Italy (Emery et al. 2018; Lugli et al. 2022). These published maps provide a basis for interpreting Sr ratios from archaeological samples. However, awareness of the diverse range of possible influences on bioavailable and non-bioavailable Sr isotope ratio composition is essential (e.g. Bentley 2006; Frei and Frei 2013; Maurer et al. 2012; Price et al. 2002; Slovak and Paytan 2012). The most significant limitation in our case study area is that the published maps are based on the interpolation or modelling

of $^{87}\text{Sr}/^{86}\text{Sr}$ values from a restricted dataset of samples, and only a few samples have been collected from the alpine highland areas (Emery et al. 2018; Willmes et al. 2014). This lack of alpine coverage limits the interpretations in terms of animal mobility and provenance. Moreover, identifying the stock's possible mobility patterns is particularly challenging across complex geology that comprises a significant diversity of rock types and erosion processes, such as the Alpine regions (Peters et al. 2017). For these reasons, complementary methods should be used to investigate herding strategies in the study area. In the absence of suitable references to estimate the local Sr ratio, the $^{87}\text{Sr}/^{86}\text{Sr}$ values from dentin can be used as a proxy for the on-site signature (Budd et al. 2000; Reitmaier et al. 2018). Whereas this approach, combining enamel and dentine $^{87}\text{Sr}/^{86}\text{Sr}$ values, allows us to distinguish different herding strategy patterns: autochthonous, mobile and allochthonous animals, identifying a specific source of provenance/destination remains unachievable, and we can only disprove a source hypothesis. Indeed, different possible geographic areas may have similar bioavailable Sr isotope ratios, limiting identifying the provenance/destination source.

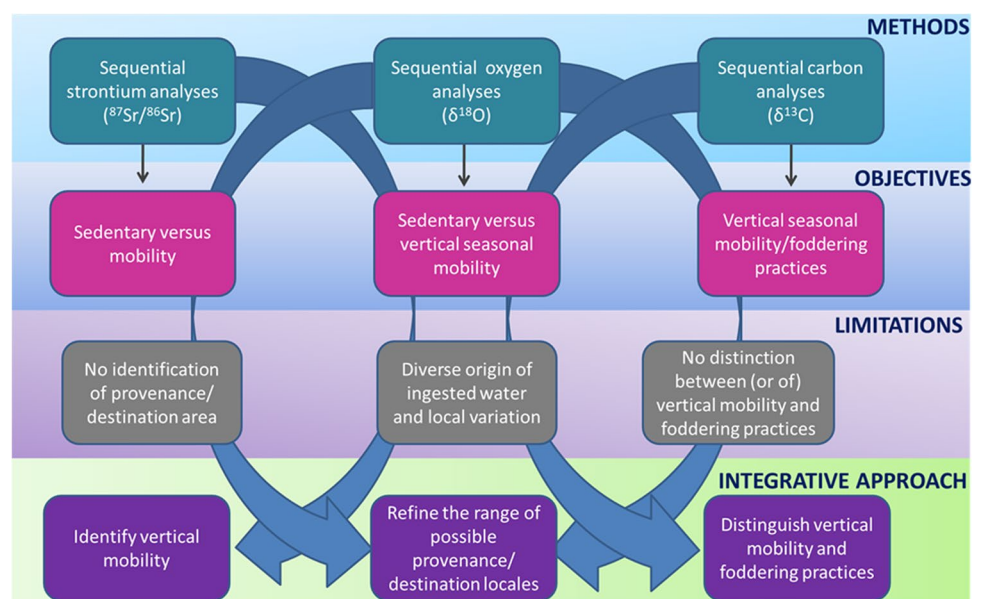
With a view to validating, or at least identifying, probable zones for the origin and destination of animals, the strontium information can be combined with another provenance-based isotope, such as the stable oxygen isotope ratio $\delta^{18}\text{O}$ (Kern et al. 2014; Longinelli and Selmo 2003; Rozanski et al. 1993; Siegenthaler and Oeschger 1980). Variations of meteoric $\delta^{18}\text{O}$ values, especially in relation to regionally specific environmental conditions, render the interpretation of oxygen isotope ratios difficult, especially when assessing animal mobility. For example, the rainfall across lowland

plains and mountains possesses different $\delta^{18}\text{O}$ values (Longinelli 1984). Despite this, the analyses of tooth-enamel oxygen isotope ratios, combined with $^{87}\text{Sr}/^{86}\text{Sr}$ values, should help identify animal mobility along an altitudinal gradient and thus reduce the number of hypotheses for destination/provenance areas.

A crucial complementary study comprises coupled intra-tooth sequential oxygen and carbon isotopic analyses to provide information about herding strategies, especially foddering practices and vertical mobility (Balasse et al. 2012a; Knockaert et al. 2018; Makarewicz et al. 2017; Tornero et al. 2020; Sierra et al. 2021; Tejedor-Rodríguez et al. 2021). The $\delta^{13}\text{C}$ values contained in herbivore enamel apatite reflect the carbon isotope composition of consumed plants, which is mainly controlled by photosynthetic pathways (Bender 1971; Farquhar et al. 1989) but also by temperature (Diefendorf et al. 2010; Hartman and Danin 2010; Smedley et al. 1991), aridity (Kohn 2010), altitude (Friend et al. 1989; Körner 1991; Körner et al. 1988; Morecroft and Woodward 1990) and the canopy effect in dense woodland (e.g. Drucker et al. 2008). Foddering practices and/or vertical mobility causing ruptures or differences in the expected natural seasonal variation in plants $\delta^{13}\text{C}$ can be observed via atypical patterns of covariation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences, characterised by shifts to reversed $\delta^{13}\text{C}$ sequences.

An integrated approach that combines strontium, stable oxygen, and carbon isotope ratio analyses allows us to compensate for the potential limitations present when only one method is employed in isolation from the others (Fig. 4). Consequently, the PATHWAY project investigates herding strategies and their diversity in the Western Alps from the Iron Age to medieval times. Furthermore, in order to

Fig. 4 Synthetic scheme of the sequential radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and stable isotopes $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ methods, their objectives and limitations and the benefit of an integrative approach



investigate the possible averaging of the input Sr signal in tooth enamel (Montgomery et al. 2010), we employ multi-collector inductively coupled-plasma mass-spectrometry (LA-MC-ICP-MS) strontium isotope ratio measurements along the growth axis of tooth enamel on modern transhumant sheep raised under control conditions (Domaine du Merle, Salon-de-Provence). Oxygen and carbon analyses were undertaken as part of the “AgroPaléoRepro” project (Défi Mutations alimentaires 2019 MITI CNRS et INRA, dir. Marie Balasse, UMR 7209 AASPE). These data improve the interpretation of chronology and synchronicity between strontium and stable isotope sequential analyses.

Through the seasons: identifying birth patterns through oxygen analyses

Within seasonally mobile flocks, the birthing period is a critical parameter that underpins and influences the availability of animal products (especially fresh milk), the breeder’s workload, and the management of pastoral territories (Chemineau et al. 2009; Tornero et al. 2020). For instance, summer dairy production in highland areas can require specific organisation and buildings for milking and storing dairy products (Brisebarre 2013; Carrer et al. 2015; Carrer 2016a, b; Le Couedic et al., 2016; Rendu 2003). Thus, understanding the practices associated with the control of the breeding calendar is essential for investigating pastoral system development.

In temperate Europe, sheep have a seasonal breeding cycle inherited from their wild ancestors, leading to births between late winter and spring (Chemineau et al. 2008). However, the capacity for out-of-season breeding occurs as early as the 6th millennium BCE in the Western Mediterranean (Tornero et al. 2020). Currently, in most Mediterranean-Alpine transhumant systems, the main lambing period is concentrated during the autumn to address a variety of environmental and socioeconomic constraints (Gay 1973, p. 409). For instance, in many dairy production systems, milking activities occur during autumn in lowland areas after returning from the alpine pastures, which is more convenient for labour organisation. Moreover, late autumn births provide five to six-month-old lambs for Easter celebrations, widely consumed in modern Judaeo-Christian societies. However, identifying the birthing season of past sheep flocks and their evolution still needs to be documented to better understand past pastoral communities’ socioeconomic strategies and organisation, especially in mountain areas. We can investigate these strategies by modelling the sequential intra-tooth analyses of stable oxygen isotope composition ($\delta^{18}O$) (Balasse et al. 2012b) and by comparison with modern reference sets with known seasons of births (Blaise and Balasse 2011; Balasse et al. 2017, 2020, 2023; Knockaert

2017; Tornero et al. 2018; Hadjikoumis et al. 2019). This project is tracking sheep birth seasons from the Neolithic to the Medieval period, from high-altitude sites to the Provençal plains to highlight the long history of this trait management in the area, possible differences between regional entities (Mediterranean and mountain areas, Fig. 3) and its coevolution with mobile technology pastoral systems and the Roman conquest.

While photoperiod essentially controls sheep reproduction, different parameters influence the cattle reproductive cycle, notably the physiological capacity for seasonal breeding and nutrition. Indeed, food availability is the primary driver of cattle reproduction. Therefore, the birth period is strongly linked to the annual vegetation growth cycle, leading to natural spring births. However, cows are biologically able to breed all year round (Balasse et al. 2012a, 2014). Significant supplementation, when food is scarce, can give breeders flexibility in calving strategy and animal resource management. Although we lack modern reference sets that facilitate the identification of the birthing season of past cattle, the modelling of $\delta^{18}O$ sequences measured in archaeological cattle molars allows an estimation of the birth distribution over a year and the identification of periods of animal resource availability, especially fresh milk (Balasse et al. 2021).

Identifying the presence and impact of domesticates/people at altitude

The development of sedaDNA (fauna)

The study of ancient DNA from lake sediments informs our understanding of historic human–environment interactions during the past and is a game-changer in alpine archaeology. Particularly pertinent from our perspective is our ability to identify the movement of new animal species into a landscape as part of a transhumant system and the consequences of this process for the environment.

Over the last decade, lake sediment DNA (lake sedaDNA) analysis has developed into an established tool demonstrating its potential for reconstructing past climatic, environmental and ecological changes as well as human activities and, thus, socioecosystem changes (Alsos et al. 2015; Bennett and Parducci 2006; Bissett et al. 2005; Boessenkool et al. 2014; Coolen et al. 2004; Coolen and Overmann 1998; Epp et al. 2015; Etienne et al. 2015; Ficetola et al. 2018; Giguet-Covex et al. 2014, 2019; Graham et al. 2016; Kisand et al. 2018; Lammers et al. 2019; Madeja 2015; Madeja et al. 2010; Marková et al. 2006; Matisoo-Smith et al. 2008; Pansu et al. 2015; Parducci et al. 2018, 2005; Pedersen et al. 2016). Lake sedaDNA, combined with landscape archaeology, palynology,

and anthracology, have considerable potential to reconstruct past landscape changes (vegetation cover), agro-pastoral activities and human–environment interactions at a catchment and micro-regional/valley scale (Giguet-Covex et al. 2014) but also on a larger scale by integrating several study sites. For instance, based on such a larger-scale approach, Giguet-Covex et al. (2023) proposed an altitudinal model of development of past alpine societies and agroecosystems in the North Western Alps. With lakes ranging from mid to high altitudes (874 to 2443 m a.s.l.) and latitudes (45.175 to 46.027° N), this large-scale analysis is now being expanded within the PATHWAY project and is investigating inter-valley pastoral dynamics in all the Western Alps from north to south.

DNA taphonomy—strengths and limitations

Previous work on lake sedaDNA in the Alps has revealed that some sedimentary contexts are not suitable for such analyses (i.e. contain little genetic material of interest) and that the processes behind the sediment formation and the geochemical composition are factors that influence the sedaDNA record quality (Giguet-Covex et al. 2019; Morlock et al. n.d; Giguet-Covex et al. 2023). A key finding of these studies is that erosion is an important transfer mechanism of plant and animal DNA from the catchment to the lake sediments. Lake-catchment systems characterised by high erosion are expected to be more suitable for sedaDNA analysis looking at terrestrial species. In particular, those with well-developed hydrographic networks at the catchment scale should be chosen as they cover a range of habitats. Erosion of upper soil horizons (e.g. through sheet erosion) by opposition to deeper horizons (e.g. through gully erosion or bank undercutting) was also proposed as a process favouring the records of plant and animal DNA in lake sediments (Giguet-Covex et al. 2019). Because agro-pastoral activities often favour soil erosion, we can expect a “snowball effect” (i.e. an amplifying effect) on the sedaDNA record of pastoralism and crops and thus a potential for semi-quantitative indicators of land use intensity. Recent results comparing concentrations and fluxes of spores of coprophilous fungi (*Sporormiella* sp.) and DNA from domestic herbivores highlighted the importance of high erosion dynamics in the DNA transfer and the detection capacity of livestock by the DNA approach (Giguet-Covex et al., the Holocene in correction). Because high stock-density levels can enhance erosion, sedaDNA detection from livestock may primarily reflect intense pastoral activity.

The use of lake sediment DNA to reconstruct past landscape changes and land-use history (plant and mammal DNA)

So far, most palaeogenetic work in the Alps has been carried out on mid to high-altitude lakes (> 900 m a.s.l.),

documenting pastoral activities in the *Alpages* (alpine pastures) and their livestock composition analysing mammal DNA preserved in the sediments. The first study using lake sedaDNA in this context to document animal composition was at Lake Anterne (Giguet-Covex et al. 2014). The lake is situated in the Northern French Alps at 2063 m a.s.l., and the first low-intensity pastoral activities in this region are tentatively dated to around 2900 BC. At that time, the lake sediment record showed increased erosion, decreased pine DNA, and the first, albeit minor (and possibly reflecting contamination) record of *Bos* DNA (i.e. cattle or auroch DNA). Altogether, these data might be interpreted as the deforestation of *Pinus cembra* to develop low-intensity pasturing activity with cattle, which led to the peak in erosion (Giguet-Covex et al. 2014; Pansu et al. 2015). However, this phase also corresponds to the transition to the Neoglacial period, i.e. a wetter and colder period that may have contributed to the decline of pine trees and the peak of erosion. Similarly, on this lake, due to the low detection of sheep DNA, we have to question the presence of these animals at c.1450 BC, i.e. during the Late Bronze Age, although there is a significant increase in *Plantago* sp. DNA, i.e. a plant often used as an indicator of pastoral pressure (Rey et al. 2013; Pansu et al. 2015). The interdisciplinary framework adopted by the PATHWAY project is enhancing our understanding of the appearance of cowherds and sheep flock management and the associated environmental changes. This is particularly important for periods where few archaeological sites or other data imply pastoral activity. In the Northern French Alps, the sedaDNA and archaeological evidence do complement one another for the Late Iron Age to Roman period as well as the Little Ice Age: animal DNA signals were contemporary with occupations of structures around Lake Anterne (data from P.J. Rey in Giguet-Covex et al. 2014; Rey et al. 2022). At a lower elevation, the sediment record of Lake La Thuile (874 m a.s.l., in the Massif des Bauges) revealed pastoral activity in a forested area during the Late Neolithic. Here, *Bos* sp. DNA and fir and alder support this inference (Bajard et al. 2017a, b; Giguet-Covex et al. 2019; Walsh and Giguet-Covex 2020). During the Late Iron Age, the record reveals the presence of *Plantago* sp. and *Rumex* sp., suggesting pastoral activity during this time. However, no mammal DNA has been detected, thus obliging us to consider the specific practices and/or the size of herds/flocks during this period (Giguet-Covex et al. 2019). These apparent discordances between the proxies also evidence the importance of analysing and integrating different indicators to increase the robustness of the records.

So far, the use of palaeogenetics has resulted in significant breakthroughs in our understanding of human–environment interactions in the North Western Alps (Giguet-Covex et al. 2023; Garcés-Pastor et al. 2022), starting with the identification of cattle herding within a forest environment

at low elevation during the Late Neolithic and leading to strong evidence for significant pastoral activity with sheep and cows during the Roman Period as well as evidence for their impact on soil stability leading to erosion in the Alps (Bajard et al. 2017b; Giguët-Covex et al. 2014; Sabatier et al. 2017). Moreover, lake sediment DNA analyses in this part of the Alps reveal an intensification and a change in livestock farming practices with the decrease of sheep in favour of cattle from the 11th to fifteenth century (Bajard et al. 2017a, b; Giguët-Covex et al. 2014; Walsh and Giguët-Covex 2020), possibly related to the increasing demand for alpine cheeses, butter, and milk in lowland urban areas (Aerni 1990; Dodgshon 2019). This period probably marks the start of dairy-cattle cheese production in the North Western Alps territory, while in the Provençal Alps the Late Medieval period saw an emphasis on sheep and goats (Burri et al. 2018; Unsain et al. 2023). Cattle breeding was significant in some specific areas, such as in maritime Alpes Maritimes and Camargue (Sclafert 1959; Stouff 1986). Another question that the PATHWAY project is investigating is the past animal composition in the Southern French Alps, which is only documented by late medieval archives for now.

In the montane zone, where arable agriculture is also possible, lake sedaDNA has provided insights into the history of these activities. For instance, arboriculture (pears, walnuts, plum or cherries, and grapes) was detected around Lake La Thuile from 1000 AD (Bajard et al. 2017a; Walsh and Giguët-Covex 2020). This phase of activity diversification, including the development of livestock farming, is also characterised by decreased erosion, which yielded sustainable soil resources (Bajard et al. 2017a). Because lake sedaDNA represents a local signal, contrary to pollen, which can also include a regional signal (Fig. 1), we can reliably link the erosion dynamic with the DNA-inferred landscape changes and human activities, showing that although land use intensified, soil degradation did not increase. This unexpected result may be due to terrace construction, fruit tree cultivation and/or hedge planting, which allow maintenance of the soil resource (Bajard et al. 2017a). For the first time, we can identify a mosaic, alpine landscape, or even a “terroir”, a landscape faceted by a range of different agricultural practices (Giguët-Covex et al. 2023). Combined with the zooarchaeological and historic archive data, sedaDNA supports the development of changes in the use of the landscape, including the development of pasturing. This contributes to our understanding of specific activities and allows us to elaborate hypotheses about changes in practices.

Our methodological framework is also strengthened by recognising taphonomic processes, which, while often considered to weaken a dataset’s quality or integrity, may contribute to our identification of certain pastoral practices and/or animal behaviour (Graham et al. 2016; Giguët-Covex et al. 2019), as well as provide semi-quantitative information

on activity intensity (Giguët-Covex et al. 2023). However, to improve our knowledge of the influence of these parameters on the DNA signals, analyses of modern sediments in known contexts will be developed.

Discussion and conclusions

In summary, our aim in this contribution has been to present and problematize an analytical and interpretive framework for investigating complex pastoral systems, agricultural systems that are resilient, in the sense that they have been active for many centuries and are still significant today. Despite their resilience, our understanding of their origins is far from complete. We considered how the “exploratory” phase of research in the Alps suffered from the absence of high-quality zooarchaeological evidence, primarily due to geological substrate in high-altitude areas comprising acidic geologies. As a transhumant pastoral system is constituted by the movement of animals to and from home territories, we turned to the home areas with archaeozoological evidence, i.e. sites that were the foci of consumption. Logically, this phase involves the identification of species and the reconstruction of age profiles. As we have seen, it is essential to differentiate between sheep and goats as the exploitation of these species can be characterised by different productive and economic aims (e.g. wool exploitation from sheep). Distinguishing these species can be challenging for zooarchaeologists. Thankfully, species identification and consequent interpretations are now feasible by combining morphological criteria analysis and the ZooMS technique. Once species have been identified, we then move to flock/herd management, particularly the question of foddering and the exploitation of different pasture zones.

The managed movement of these domesticates from one pasture to another is an incredibly complex system, a system that is not only founded on exploiting the ecological characteristics or “benefits” of pastures whose productivity is underpinned by topographic and climatic configurations but is also organised via human activities via imbricated social, cultural, and legal frameworks that structure which pastures can be used by who and when. We can go some way to answering the question of pasture locations and at which time of year they were used via research on isotopic signatures. The influence of different social, cultural and legal frameworks can be reviewed via reference to ancient texts. For the medieval period, specific documents elucidate the nature of these systems and allow us to test or confirm the mobility patterns inferred from isotope data.

As a diachronic project, ranging from the Iron Age to the Medieval period, a core aim is to review changes in the characteristics of the pastoral systems, including variations in the specific activities associated with pastoralism, such

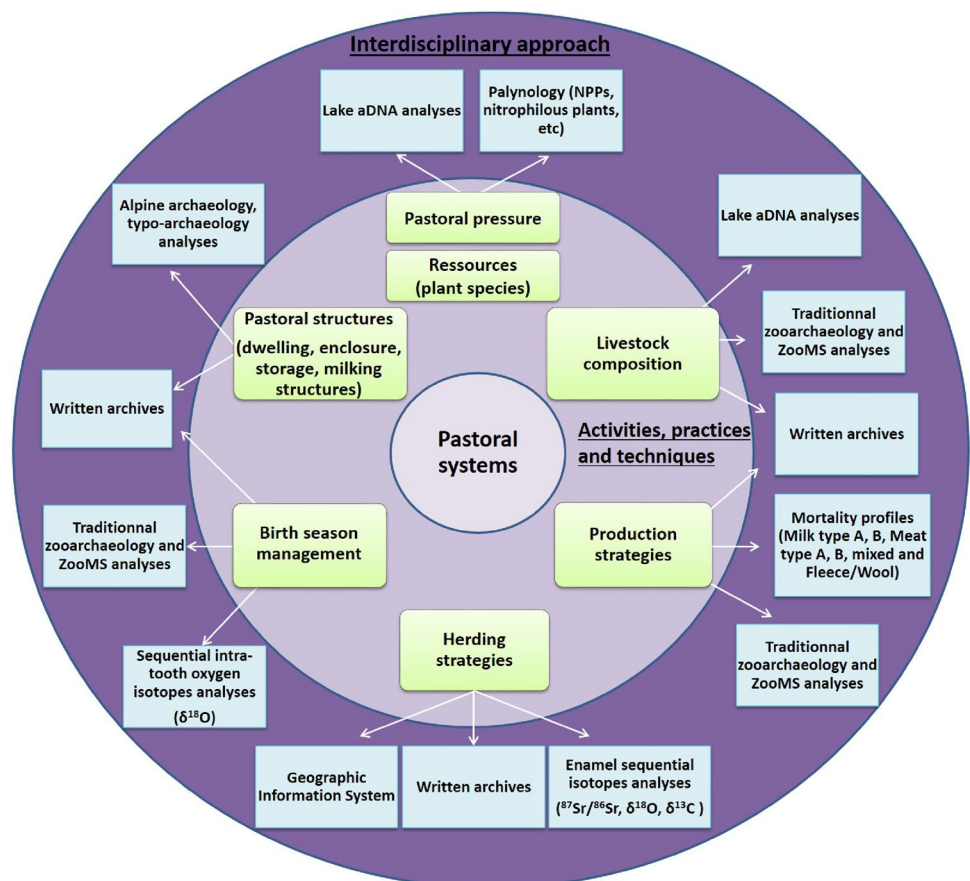
as changes in preference for certain species and their secondary products. In addition, changing patterns in the use of different pastures and the inferred density of pasturing is elucidated via the palynological and sedaDNA, which are diachronic signals extracted from lake cores. Also, the combination of existing archaeological evidence for pastoral structures, zooarchaeological and palaeoenvironmental data allows us to interrogate the probable impact of pastoralism on the landscape (Fig. 5). Ultimately, all this evidence can be used in reviewing the resilience and sustainability of this keystone agricultural system. While this project does not directly engage with analyses of material culture, we realise that specific food production practices associated with dairying can now be inferred from lipid and protein analyses, including evidence for high dairy production from the Iron Age in the Swiss Alps (Carrer et al. 2016). The development of this type of analysis, in hand with the studies of pastoral systems outlined above, facilitates the development of comparative studies of the evolution of pastoral systems: in particular, the identification of each stage, activity, practice and technique in the use of the landscape, the exploitation of animals and the exaction of both primary and secondary products.

We believe that the development of recent approaches in zooarchaeology and bioarchaeology/microbiology does

not just produce new data, but their combination significantly contributes to the range of questions that we can now answer. We are moving away from the mere description or characterisation of broad activity categories, such as pastoralism, and now engaging with the practices and techniques that constitute the pastoral system. In addition, we are constructing links between these practices and their consequences for the environment. Where possible, we aim to integrate several data types in our assessment of pastoral systems.

An example of problematic inferences from a single data type is the Col de la Traversette (2947 m, in the Southern French Alps). Here, the discovery of clostridium dated to the Iron Age within a peat profile was considered proxy evidence for Hannibal and his army (including horses with the clostridium bacteria in their guts) across this area (Mahaney et al. 2019, 2017). In fact, as the authors, albeit briefly, implied, it is far more likely that this evidence represents the repeated passage of traders, pastoralists moving across this frontier area during a chronological period when we know that pastoral activity intensified in our region. At another possible “Hannibal” pass, Lake Savine (Col du Clapier), there is sedaDNA evidence for *Bos* during the Iron Age and a more significant Roman-period presence of both *Bos* and *Ovis* (Sabatier et al. 2017; Chen 2019). The potential for

Fig. 5 A representation of the relationships between the elements and processes that constitute pastoral systems and the methods employed to elucidate these elements and processes. Centre = the pastoral system. Intermediate circle = key pastoral processes (activities, practices and techniques); interdisciplinary approaches (outer). Outer circle = associated methods



the combined use of biomarkers, pollen, non-pollen palynomorphs, and sedaDNA in identifying the presence of pastured animals and their consequent impact on high-altitude pastures is significant. The inference of pastoral practices is an example of how integrating traditional archaeological, historical and bioarchaeological methods, including zooarchaeology and isotope research, is changing how we investigate and interpret complex agropastoral systems and the mountain economy.

Author contributions All authors contributed to the conception and structuring of the manuscript. While KW designed the overarching project and consequent manuscript. The manuscript is, for the most part, a & position piece & articulating a theoretical and integrated methodological framework for the study of ancient pastoral, transhumant systems. Those sections that do present existing or new data were developed by JK, KD and CG-C. The first draft of the manuscript was written by KW, JK, KD and C-GC, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. KW is responsible for the overall conceptualisation of the research project and the structuring and writing of c. 50% of the manuscript. The underlying AHRC project was designed by KW, AP, CG-C and SB. The Aix-Marseille (AMIDEX) funding and project development was undertaken by FM and PM. They also contributed to the structuring of this manuscript and part of the writing. The specific methodological sections were researched and written by JK, DU and DO (archaeozoological approaches); JK (isotope analyses); sedimentary DNA analyses (KD and CG-C. The historical documents section was researched and written by DU and SB. All five figures were jointly produced by KW, JK, KD, C-GC, FM and DU.

Funding This collaborative project is part of the UK “PATHWay Programme” (Dir. Walsh K.) funded by the Arts and Humanities Research Council (AHRC) (grant number: AH/P013554/1), and the French project (Dir. Mocchi F., Magniez P.) received support from the French government under the France 2030 investment plan, as part of the Initiative Excellence Aix-Marseille Université-A*MIDEX (AMX-18-INT-032).

Declarations

Competing interests The authors declare no competing interests.

Ethics approval None apply.

Consent to participate None apply.

Consent for publication All authors have participated in the production of this manuscript, and individual content can be obtained if required.

Data availability This article is a position paper that does not refer directly to new (unpublished) raw data.

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